UDC 551,575.1:551.578.4:551.511.33:551.521.32(798)

HEAT BALANCE STUDIES DURING AN ICE-FOG PERIOD IN FAIRBANKS, ALASKA

GERD WENDLER

Geophysical Institute, University of Alaska, College, Alaska

ABSTRACT

Ice fog, which is in a way similar to a dense cirrostratus cloud near the surface, occurs in Fairbanks when the temperature drops below -35° C. The heat balance of two stations, one below the ice fog in the valley and the other one on Birch Hill above the ice fog, are compared for the longest cold spell in winter 1966/67. The valley station shows a relatively small radiative loss of 47 cal cm⁻² day⁻¹, as the ice fog shelters the surface against a highly negative longwave radiation balance. The energy for compensation of this loss comes mostly (25 cal cm⁻² day⁻¹) out of the soil. On Birch Hill the radiative loss (124 cal cm⁻² day⁻¹) is nearly three times larger, mostly due to the smaller amount of the incoming long-wave radiation, and here the sensible heat flux (102 cal cm⁻² day⁻¹) provides most of the energy.

1. INTRODUCTION

Ice fog is a form of low temperature air pollution. It is observed to form at Fairbanks (64°50' N., 147°40' W.) when the temperature falls below -35° C; at temperatures under -40°C the fog becomes quite thick. As the Fairbanks area is surrounded on three sides by hills (fig. 1), a strong inversion is built up in winter, caused by radiation cooling of the surface and gravity drainage of cold air into the low-lying areas. In midwinter the radiation balance even during the noon hours remains negative, as the daylight period is short and the angle of the sun low. In the absence of strong gradient winds, the conditions for the growth of the inversion are favorable as there is little forced convection. The radiation balance can become slightly positive, if the cloud amount is high and the radiative temperature of the clouds is higher than that of the surface. Low cloud amount is also very important for the growth of the inversion.

Cold spells during which ice fog occurs are, therefore, normally associated with high-pressure situations over Central Alaska (Bowling, 1967), and with resulting low cloud amount and small wind velocities. The inversion starts at the surface and builds up to increasing height with continued duration of the cold spell (Benson, 1965). The moisture, produced by man through heating, automobiles, and power plants, stays in the layer near the ground, as the very strong inversion reduces turbulence in the lowest layer. At low temperatures the air cannot contain much water in the vapor phase; therefore, most of the water vapor condenses. If the temperature reaches the spontaneous freezing point for water (about -40° C), the droplets freeze and the ice fog occurs. It can become very dense, so that visibility is less than 30 m. The vertical extension is quite small, normally about 10 m, though for long-lasting cold spells it may reach 30 m. The ice fog is hazardous to the health and very dangerous for street and air traffic. Figure 2 shows Fairbanks under an ice fog. It may be seen that the air pollution becomes more dense in the center of the town. Studies of ice fog have been done by the above-mentioned authors and also by Robinson et al. (1955, 1956, 1957), Benson et al. (1965), Kumai (1964), Politte (1965), and Ohtake (1967).

2. INSTRUMENTATION AND PERIOD OF ICE FOG

During the winter 1966/67 an extensive micrometeorological program was carried out in the Fairbanks area. This depended largely on observations made by the U.S. Army Meteorological Team at Ft. Wainwright, whose efforts in keeping the equipment running during a time with a maximum temperature below -40° C are to be greatly commended. The measurements of the radiation and heat balances for the valley (under the ice fog) and on Birch Hill (above the ice fog) are of special interest. A comparison of these two stations was carried out for the main cold spell (December 6 to 13) of the winter 1966/67. The ice fog appeared on the 6th and was maintained during the 7th to the 12th, in which period the temperature in the valley never exceeded -40° C. On the 13th the fog dissipated. The meteorological situation during each of these cold days was very similar and will be described below.

There were several stations in the valley (elevation about 130 m) and one on Birch Hill (332 m) measuring the temperature and wind profiles, wind direction, humidity, surface temperature, profile of snow temperature, snow depth, atmospheric pressure, and radiation. The hourly cloud conditions were recorded at the Weather Bureau at the International Airport, and the temperature profile of the snow cover and its density were measured at the Experimental Farm at the University of Alaska.

The temperature profile and wet-bulb temperature were measured with ventilated thermocouples. However, the values of the wet-bulb temperature during the cold spell are missing. The surface temperature and the soil temperature were recorded with thermocouples. The values of the surface temperature are probably inaccurate especially during hours of bright sunshine, as the thermocouple was unsheltered. Continuously recording fan anemometers at different heights were used for the measurement of the wind profile, and the wind direction was given to the nearest of 16 points of the compass. The

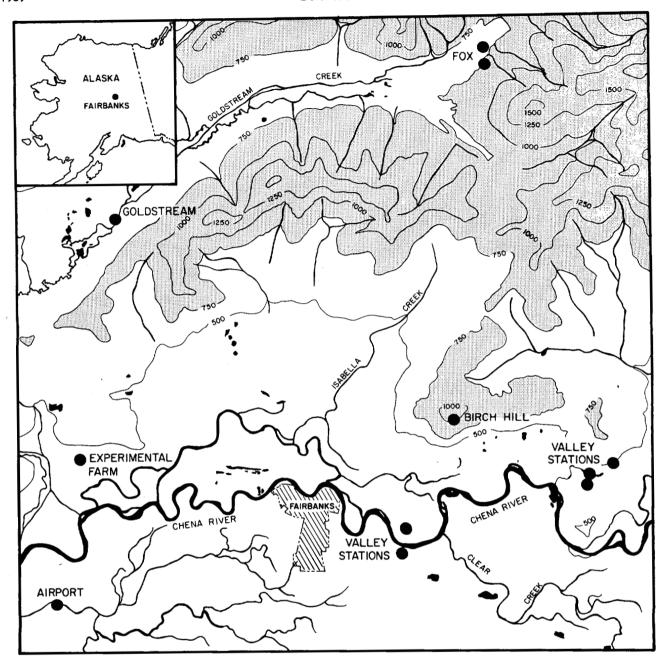


FIGURE 1.-Fairbanks, Alaska, area.

atmospheric pressure was measured with microbarographs, and the radiation studies were carried out with ventilated Beckman and Whitley radiometers. Unfortunately, the use of the latter instrument prevents a distinction being made between long- and short-wave radiation.

3. METEOROLOGICAL CONDITIONS DURING THE PERIOD OF OBSERVATIONS

GENERAL CONDITIONS

From the 6th to the 12th of December, a high-pressure system of varying intensity was located over the Yukon Territory with a ridge extending to the west and north-west over Central Alaska. By the 13th, the day the ice fog ended in Fairbanks, this system had weakened with the center then located to the east near Great Slave Lake.

The highest daily station-level pressure (nearly 1010 mb) was observed in Fairbanks on the 8th of December (fig. 3, curve E). Thereafter, a steady fall of pressure was observed with the minimum (983 mb) at the end of the period on the 13th. There was little cloudiness during the whole time. The airport observed values of slightly less than 30 on the average (fig. 3, curve C). Actually this value is far too high, as most of the cloudiness that was observed consisted of ice fog, which drifted at times from the town to the airport (10 km distant) or was formed at the airport itself. Estimates of the amount of cloudiness that really occurred are difficult, as cloud observations are: impossible when very dense ice fog restricts upward visibility. Furthermore, such observations are uncertain during nighttime, which existed during about 80 percent of the whole period of ice fog. Therefore, the little cloudiness



FIGURE 2.—Fairbanks and Ft. Wainwright, Alaska, situated under a layer of ice fog. Photo by C. Benson.

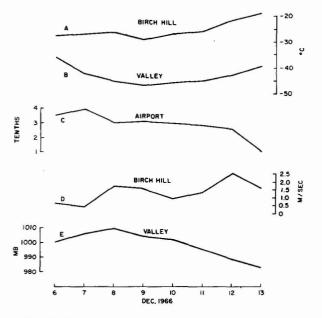


FIGURE 3.—Daily averages of meteorological elements, Fairbanks, Alaska, winter 1966/67.

on the 13th is rather a sign that on this day there was no ice fog at the airport than that the cloudiness was really below average.

Winds during the period were very light. In the valley, calms were often observed up to the highest point of

measurements (16 m above ground). Even on Birch Hill the wind was light with an average of 130 cm sec-1 at 8 m above ground (fig. 3, curve D). The highest wind velocity (250 cm sec⁻¹) was observed on the 12th, which advected warmer air to the Fairbanks area. The daily mean temperatures for Birch Hill and the valley are given in figure 3, curves A and B. During the time from the 7th to the 12th of December, the valley temperature stayed steadily below -40° C with an average of -44.6° C. The mean temperature for the same period on Birch Hill was -27.7°. This results in an average inversion of 16.9°C over a 199 m of altitude difference. The course of temperature on Birch Hill is similar to that in the valley. The coldest day was observed for both stations on the 9th, with a mean of -46.7° C in the valley; thereafter, a slow warming occurred at both stations. Calculations of the average temperature of the air lying in the valley by using the atmospheric pressure of the stations also gave, as expected, the lowest value on the 9th.

DAILY VARIATIONS

The daily variations of temperature (fig. 4, curves A and B) for the time from the 7th to the 12th of December were small. The mean daily variation of the valley station was 0.8°C with a maximum at 1300 Lst, and the minimum in the morning around 0700 Lst. The daily course was very smooth, which is evidently due to the fact that the valley station is situated under the ice fog. Furthermore,

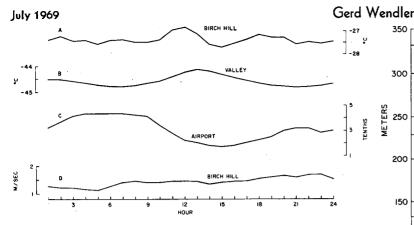


FIGURE 4.—Daily mean course of meteorological elements for a 6-day period, Fairbanks, Alaska, winter 1966/67.

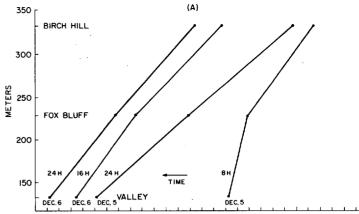
advection of air of different temperature is of minor importance, as there is no, or very light, wind.

On Birch Hill the daily course of temperature exhibits more fluctuation, which is a result of higher turbulence, advection, and the greater influence of the short-wave radiation. The daily variation is also small (0.9°C), the maximum temperature being observed at noon. Temperatures were higher in the evening than in the afternoon, which was due to the slightly higher wind speed during this time of the day (fig. 4, curve C). Otherwise, the wind speed does not show a regular daily course. The cloudiness (fig. 4, curve D) shows a considerable daily variation, with the maximum in the early morning and the minimum in the afternoon. These data really show much more closely the daily variation of the ice fog than that of cloudiness at the airport. As there is more turbulence during daytime, partly due to more air traffic during this time, the ice fog cannot exist as easily as during nighttime.

INVERSION

Benson (1965) pointed out that the inversions connected with ice-fog situations are among the strongest that can be found in any part of the world. In figure 5 the initial strengthening of the inversion and its partial destruction at the end of the ice-fog period are shown. The temperature of Fox Bluff (elevation 228 m), which is situated about 16 km north of Fairbanks, as well as the temperature on Birch Hill will be unequal to the temperature of the free atmosphere above Fairbanks. Nevertheless, the differences are believed to be relatively small.

On the 5th of December (fig. 5A), the inversion of 7.2°C was not particularly strong for the 199-m altitude difference between the valley and Birch Hill for winter conditions in Fairbanks. In the next 16 hr, the negative radiation balance cooled the valley from —27.8°C to —38.9°C—a rate of 0.75°C hr⁻¹. On Birch Hill the cooling was less than 2°C for the same time, which strengthened



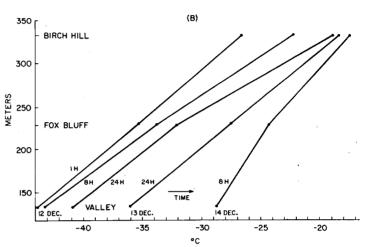


FIGURE 5.—The development and destruction of the inversion in the Fairbanks, Alaska, valley for a cold spell in winter 1966/67; (A) December 5 and 6; (B) December 12, 13, and 14. The time intervals were chosen of unequal length to avoid the use of values during daylight time; otherwise, the daily course of the temperature would disturb the picture.

the inversion to 16.6°C. Some 16 hr later, the cooling in the valley was small (1.7°C), as in the meantime some ice fog had been established, which sheltered the surface against a greater loss of long-wave radiation. The cooling of higher layers above ground became more pronounced, as can be seen at the Birch Hill station (7.2°C). After an additional 8 hr, the cooling at all altitudes was about the same and was relatively slow. In summary, it may be said that the cooling started at the surface and proceeded later to higher layers. The warming observed at the end of the ice-fog situation started at higher layers and slowly went down to the ground (fig. 5B). The advection of warm air naturally influenced first the higher layers and later on the very cold and stable air near the ground. The temperature gradient on the 12th of December at 0100 LST was typical for the first time with ice fog. During the day warmer air moved in, which warmed the surface by only 2.8°C, but Birch Hill by 7.8°C. This warming in the higher layers steepened the inversion by 5°C to

Table 1.—Radiation balance (cal cm-2 day-1) of the Fairbanks area

Station	Date						Average
	7	8.	9	10	11	12	
Valley Birch Hill	-43 -133	-52 -145	-50 -119	-44 -105	-48 -113	-46 -131	-47 -124

22.2°C. In the next 32 hr, the warm air reached the bottom of the valley, and a temperature rise of 12.2°C was observed. The warming on top of Birch Hill (1.3°C) for the same period was comparatively small, and this partly weakened the inversion.

4. COMPUTATION OF THE HEAT BALANCE

The following simplified equation holds for the heat balance of a nonmelting surface, under the assumption that no advection of air occurs:

$$S + B + L + V = 0$$

where:

S denotes the radiation balance,

B the heat flow within the soil or snow,

L the sensible heat flux, and

V the latent heat flux.

These individual terms may be either positive—i.e., they transfer heat to the surface—or negative, meaning that they deduct heat from the surface.

RADIATION BALANCE

The radiation balance was measured, as mentioned before, with ventilated Beckman and Whitley radiometers. This kind of instrument makes a distinction between longand short-wave radiation impossible. However, because in the present case the nights last for about 20 hr and during the remaining 4 hr the short-wave radiation is of minor significance due to the low angle of incidence of the sun, this is not a very serious drawback. In table 1, the radiation balance is given in daily values. Hourly values are not given, as there was not found to be a great variation in the daily course. The radiation balance is negative for all daily and all hourly values at both stations. The mean value for the valley is 77 cal cm⁻² day⁻¹ less negative than that of Birch Hill. The greater loss on Birch Hill is due both to the smaller amount of incoming long-wave radiation and the greater amount of outgoing long-wave radiation due to the higher surface temperature.

The ice fog shelters the valley against great losses of long-wave radiation. The large difference is completely an effect of the long-wave radiation as the short-wave radiation can be only positive; and due to some absorption in the ice fog, smaller values would be found in the valley than on Birch Hill.

The variations from day to day for both stations are relatively small, which is due to a fairly constant surface temperature, cloudiness, and, for the valley station, approximately constant density and vertical extent of the ice fog.

The average daily courses show also only slight variations. For the valley station, values between -1.8 and -2.2 cal cm⁻² hr⁻¹ were found with an average of -2.0 cal cm⁻² hr⁻¹. On Birch Hill the average was -5.2 cal cm⁻² hr⁻¹, ranging from -4.7 to -6.0 cal cm⁻² hr⁻¹.

A very rough estimate of the thickness of the ice fog may be made using the radiation differences of both stations. Little is known about the absorption and diffraction characteristics of infrared radiation in a cloud of ice crystals. Cirrostratus clouds would be the most suitable to compare with, but investigations of this type of cloud are difficult. Under several simplifying though rather unreal assumptions, an estimate was made of the ice-fog depth, in this particular case yielding a mean value of 9 m.

Benson (1965) quotes a vertical extent of about 10 m for previous ice-fog events. This depth can increase up to 30 m in a long ice-fog period. For a very rough kind of estimation, the agreement can be regarded as quite satisfactory. It might be pointed out here that, with more sophisticated radiation equipment at two levels, it would be possible to investigate further the radiation characteristics of ice crystals for particular spectral wavelength bands in both visible and infrared regions. This would be a unique way of measuring such characteristics of ice-crystal clouds, which normally occur only at great heights in the atmosphere.

HEAT FLUX OUT OF THE GROUND

During a cold spell the air is normally warmed by the surface; therefore, the heat flux B in the ground is directed to the surface, i.e., positive. In figure 6 the temperature of the snow cover and the soil is given for certain intervals; figure 6A shows the data of the valley and figure 6B that of Birch Hill. The intervals shown are not exactly coincident in time, as the warming occurred on Birch Hill earlier than in the valley. The cooling of the soil in the valley was much greater due to the steeper temperature gradient in the snow cover there than on Birch Hill. This was itself due essentially to the lower surface temperature in the valley.

There are two ways of calculating the heat flux from the soil to the surface. In one method the change of temperature in the ground over a certain time is used, while in the other the temperature gradient is employed. In the present case the former method can be described by the following expression:

$$B = (\rho c)_{sn} \int_0^{z_1} \Delta T_1 dz + (\rho c)_s \int_{z_1}^{\infty} \Delta T_2 dz$$

where:

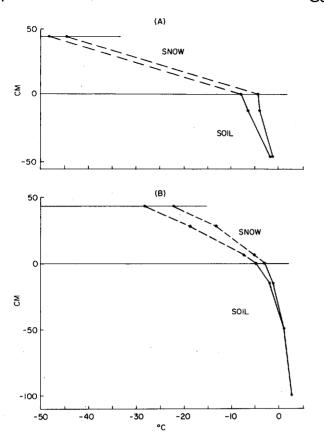


FIGURE 6.—The temperature change in soil and snow for two Alaskan stations, (A) valley and (B) Birch Hill, during a cold spell in winter 1966/67.

 $(\rho c)_{sn}$ denotes specific heat per unit volume of snow,

 $(\rho c)_s$ specific heat per unit volume of soil,

 z_1 depth of snow cover,

 ΔT_1 temperature change in the snow cover, and

 ΔT_2 temperature change in the soil.

Values for $(\rho c)_{sn}$ can be calculated and for $(\rho c)_s$ have to be assumed, as measurements are not available. According to the literature (DeVries, 1963; Geiger, 1965), a reasonable value for snow of low density is 0.15 cal cm⁻³ (deg C)⁻¹ and for heavy soil 0.45 cal cm⁻³ (deg C)⁻¹. By planimeter measurement of the temperature profiles and some extrapolation for the valley station, B can be determined.

The second method uses the temperature gradient. It can be described by the expression

$$B = \lambda (dT/dz)t$$

with λ as heat conductivity and t the time. In this expression, B and λ are not known. By using the values of B found by the first method, the following values of λ for the snow cover result:

$$\lambda_{\it valley}\!=\!2.9\!\cdot\!10^{-4}\;{\rm cal}\;{\rm cm}^{-2}\;({\rm deg}\;{\rm C})^{-1}\;{\rm sec}^{-1}$$

and

 $\lambda_{Birch\ Hill} = 2.6 \cdot 10^{-4}\ cal\ cm^{-2}\ (deg\ C)^{-1}\ sec^{-1}$.

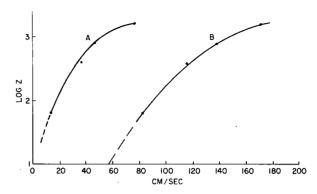


FIGURE 7.—The mean wind profile for a 6-day period. Valley station (A), Birch Hill (B), Fairbanks, Alaska, winter 1966/67.

This difference of 11 percent in the values of λ could be real, as Weller and Schwerdtfeger (1968) found a dependence of the heat conductivity on the temperature of about 0.6 percent (deg C)⁻¹. As the snow temperature of the two sites differed by about 15°–20° C, the agreement with the measurements of the above-mentioned authors is quite good. Therefore, the heat fluxes were calculated by using the second method and employing different values of the heat conductivity of snow for the two stations. The following mean daily values were found for the 6-day period:

$$B_{valley}{=}25~{
m cal}~{
m cm}^{-2}~{
m day}^{-1}$$

and

$$B_{Birch\ Hill} = 13\ \mathrm{cal\ cm^{-2}\ day^{-1}}.$$

The value found for the valley is about twice as high as that of Birch Hill. Nevertheless, even the value of the heat flux in the valley is relatively small, as snow with low density is a good insulator and prevents rapid temperature changes in the soil.

SENSIBLE AND LATENT HEAT FLUXES

The sensible and latent heat fluxes can be calculated with the aid of Prandtl's relation (Lettau, 1939, 1949; Prandtl, 1956). The windspeed, which was observed in the valley, is very low. A mean value of 31 cm sec⁻¹ was found for a height of 360 cm above the surface. This low mean wind velocity is typical of ice-fog situations (Benson, 1965). In figure 7, curve A gives the mean wind profile with altitude for the 6-day period. The value at 60 cm above ground is poor, as it is based on only 1 day of observations (7th of December). During the rest of the time the wind was too light at this height to record on the instrument or the anemometer was inoperative due to freezing. Therefore, the windspeed was calculated using the relation to the wind observations at greater heights from this 1 day.

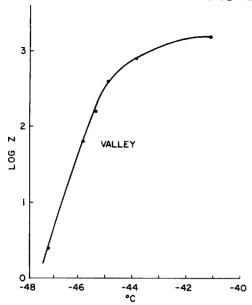


FIGURE 8.—The mean temperature profile for a 6-day period at valley station, Fairbanks, Alaska, winter 1966/67.

The wind profile does not show a linear dependence on the logarithm of the altitude. The value at 1600 cm above ground shows much too high a value caused by the strong inversion (Ullrich, 1967). This results in a dependence of the friction velocity on the height. As in this case the balance should be calculated for the surface, the lower three values (60 cm, 360 cm, and 760 cm above the surface) were used, which show a fairly logarithmic course. By using these values, a roughness parameter of 2.6 cm was obtained. This is an extremely high value compared with those given in the literature (e.g., Ambach, 1963). It is thought to be due to a rougher surface caused by some brushwood, which broke through the snow cover, while Ambach's values are valid for the smooth snow-covered ice sheet of Greenland.

The friction velocity (2.5 cm sec^{-1}) is very small due to the low wind velocities. For the snow-melting period, values about three times higher were found in the same valley (Wendler, 1967). This resulted in an exchange coefficient A, at height 5 cm, of 1.01 gm cm⁻¹ sec⁻¹.

The temperature profile (fig. 8) also does not show a linear course with the logarithm of the height. The temperature values at 760 and 1560 cm above the surface are particularly out of profile. This is a result of the radiative processes. As these points are near the upper extension or even out of the ice fog, a bigger loss in long-wave radiation than at the surface can be expected. As in every layer the sum of all heat fluxes equals zero, the higher temperature (fig. 8) and wind velocity (fig. 7, curve A) will cause a higher sensible and latent heat flux, which is needed to retain the equilibrium. The lower four values, which show a fairly linear course with the logarithm of height, were used. Calculations were made for the height

of 5 cm, as at this altitude the correction for a nonadiabatic temperature gradient is small. A correction of only 1 percent in A was found. Using the values given above, an average sensible heat flux of 19 cal cm⁻² day⁻¹ was found, which is a very low value considering the steep temperature gradient above the surface. Such a low value is, therefore, to be attributed to the low wind speed.

The calculation of the latent heat flux is inaccurate, as measurements of the humidity were missing. The ventilated wet-bulb thermometers did not work satisfactorily during the extreme cold spell. The assumption was made that at all heights water vapor saturation occurred, which is close to the truth during periods of ice fog. The moisture content becomes then only a function of temperature. As at low temperatures only little water vapor can stay in the air, the computed gradient was also low. Calculations analogous to the sensible heat flux were made using the same value of the eddy diffusivity. This resulted in a value of 1 cal cm⁻² day⁻¹, which is an extremely low value, considering that during all the time condensation was occurring. Even an error of 100 percent in the water vapor gradient would affect the heat balance study very little.

The sensible and latent heat flux on Birch Hill was also calculated. The wind speed observed on Birch Hill was more than three times stronger than in the valley (fig. 7, curve B), but the average (116 cm sec⁻¹) for 360 cm above the surface is still low. The velocity does not show a linear dependence on the logarithm of height. The roughness parameter depends on the method of extrapolation of the wind profile curve. Values about 0.5 cm are found. This results in a friction velocity of 7 cm sec⁻¹.

The temperature profile was not measured at this station. Only the surface temperature and the temperature 110 cm above the surface were recorded. It is possible to calculate, at least roughly, the sensible heat flux using these data. However, attempts that were made showed that the heat flux calculated in this way was much too small to balance the heat budget equation. This means that the measured temperature gradient was not sufficiently steep. This might be due to the fact that the thermocouple with which the surface temperature was measured was unsheltered. This resulted in a surface temperature that was too high during the time with short-wave radiation. Furthermore, the thermocouple might be slightly covered with snow, which would also give too high a surface temperature or too weak a temperature gradient.

Therefore, the total of the sensible and latent heat fluxes was equated to the sum of the radiation balance and the heat flux out of the soil. The Bowen ratio was used to determine the ratio of sensible to latent heat flux (Sverdrup, 1936; Kraus, 1958; Tajchman, 1967). This method has the disadvantage that the data do not control each other, and the heat balance must equal zero. As in the valley and on Birch Hill, the same instrumentation and method were used to calculate both the heat flux out of

Component	Valley	Birch Hill
Radiation_ Heat flux of soil	$ \begin{array}{r} -47 \\ +25 \\ +19 \\ +1 \\ -2 \end{array} $	$ \begin{array}{r} -124 \\ +13 \\ +102 \\ +9 \\ 0 \end{array} $

the soil and the radiation balance; and, as furthermore a relatively good agreement was found in the heat balance for the valley, this way of calculating the sensible and latent heat is thought to be reasonable. This method results in a sensible heat flux of 102 cal cm⁻² day⁻¹ and a latent flux of 9 cal cm⁻² day⁻¹. The latent heat flux is here also relatively higher than in the valley, but as it contributes only about 9 percent of the total turbulent heat fluxes it is still quite unimportant.

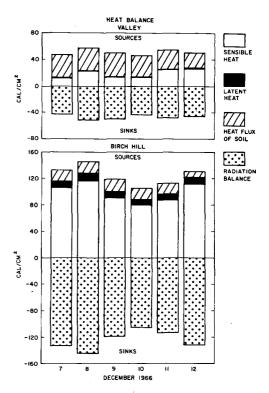
5. HEAT BALANCE

The mean daily values of the heat balance are given in table 2. In the valley the heat balance does not balance by 2 cal cm⁻² day⁻¹, which would be 4 percent of all negative components. This disagreement is acceptable, as errors of all components up to 10 percent can be considered as quite possible. The sum of the sources and sinks on Birch Hill equals zero of course. The possible error will be of the same order as for the measurements in the valley.

The heat balances look quite different for the valley and hill stations. In both cases the only loss is in the radiation balance, but it is about three times higher on Birch Hill. In the valley the biggest source is the heat flow out of the soil, while the sensible and latent heat fluxes are of minor importance due to the low wind. On top of Birch Hill it is the opposite. There, the sensible heat flux exceeds the heat flux out of the soil due to stronger wind and weaker temperature gradient in the snow cover. In figure 9 the daily components of the heat balance are given. The changes from day to day are relatively small, and the average value closely represents the individual daily values.

6. CONCLUSION

When the cloud amount is low, the greatest loss of energy at the surface during winter occurs in high latitudes by long-wave radiation. In Fairbanks, where there is a relatively high population (about 30,000), much water vapor is produced and ice fog is formed during the time of extreme cold spells. This transfers the layer of the greatest radiative loss from the surface to the upper extension of the ice fog, and this is clearly shown by heat-balance studies above and below the ice fog.



519

FIGURE 9.—The heat balance at the snow surface for an Alaskan valley station situated under the ice fog and for Birch Hill above the ice fog.

ACKNOWLEDGMENTS

The author is indebted for the great assistance given by the U.S. Army Meteorological Team, Ft. Wainwright, Alaska, on whose data this study is almost exclusively based. Dr. A. Kallio and Dr. C. Benson, both of the University of Alaska, provided some temperature and density data of the snow cover, and Mr. J. Hanson, U.S. Weather Bureau, Fairbanks, made the hourly values of cloudiness available. Finally I wish to acknowledge the very helpful discussions with Mr. Neil Streten and Dr. G. Weller, both of the University of Alaska. This work was supported by State of Alaska funds.

REFERENCES

Ambach, W., "Untersuchungen zum Energieumsatz in der Ablationszone des Grönländischen Inlandeises," (Investigations on the Energy Exchange in the Ablation Zone of the Greenland Icecap), Meddelelser om Grønland, Vol. 174, No. 4, 1963, C.A. Reitzels Forlag, Copenhagen, 311 pp.

Benson, C. S., "Ice Fog: Low Temperature Air Pollution, Defined With Fairbanks, Alaska as Type Locality," *Geophysical Institute Report* UAG-R-173, University of Alaska, College, Alaska, Nov. 1965, 78 pp.

Benson, C. S., Gotaas, Y., Francis, K. E., and Murcray, W. B., "Ice Fog Studies in the Fairbanks Area 1961-1963," Proceedings of the 15th Alaskan Science Conference, University of Alaska, College, Alaska, 1-4 September 1964, Alaska Division of the American Association for Advancement of Science, Mar. 1965, p. 89. Bowling, S. A., "A Study of Synoptic-Scale Meteorological Features Associated With the Occurrence of Ice Fog in Fairbanks, Alaska," M.S. thesis, Geophysical Institute, University of Alaska, College,

Alaska, May 1967, 141 pp.

- DeVries, D. A., "Thermal Properties of Soils," Physics of Plant Environment, North-Holland Publishing Co., Amsterdam, 1963, pp. 210-235.
- Geiger, R., The Climate Near the Ground, Harvard University Press, Cambridge, Mass., 1965, 611 pp.
- Kraus, H., "Untersuchungen über den nächtlichen Energietransport und Energiehaushalt in der bodennahen Luftschicht bei der Bildung von Strahlungsnebeln," (Investigations on the Nocturnal Energy Transport and Energy Budget in the Air Layer Next to the Ground in Connection with Radiation Fog Formation), Berichte des Deutschen Wetterdienstes, Vol. 7, No. 48, German Weather Service, Offenbach am Main, West Germany, 1958, 25 pp.
- Kumai, M., "A Study of Ice Fog and Ice-Fog Nuclei at Fairbanks, Alaska, Part I," Research Report 150, U.S. Army Materiel Command, Hanover, N.H., Aug. 1964, 27 pp.
- Lettau, H., "Atmosphärische Turbulenz," (Atmospheric Turbulence), Akademische Verlagsgesellschaft, Leipzig, 1939, 283 pp.
- Lettau, H., "Isotropic and Non-Isotropic Turbulence in the Atmospheric Surface Layer," *Geophysical Research Papers*, No. 1, U.S. Air Force Cambridge Research Laboratories, Mass., Dec. 1949, 86 pp.
- Ohtake, T., "Alaskan Ice Fog: Pt. 1. A Progress Report of Ice Fog Research," Proceedings of the International Conference on Low Temperature, Sapporo, Japan, August 14-19, 1966, Vol. 1, Institute of Low Temperature Science, Hokkaido University, Japan, 1967, pp. 105-118.
- Politte, F. E., "Minimum Ice Fog Visibility at Low Temperatures at Eielson, AFB, Alaska," Eielson Air Force Base, Alaska, 1965, 5 pp., (unpublished manuscript).
- Prandtl, L., Führer durch die Strömungslehre, (Guides Through the Theory of Flow), Vieweg und Sohn, Braunschweig, West Germany, 1956, 407 pp.

- Robinson, E., and Bell, G. B., Jr., "Low-Level Temperature Structure Under Alaskan Ice Fog Conditions," Bulletin of the American Meteorological Society, Vol. 37, No. 10, Dec. 1956, pp. 506-513.
- Robinson, E., Bell, G. B., Jr., Thuman, W. C., St. John, G. A., and Wiggins, E. J., "An Investigation of the Ice Fog Phenomena in the Alaskan Area," *Final Report*, Contract No. AF 19(122)-634, Stanford Research Institute, Stanford, Calif., June 1955, 157 pp.
- Robinson, E., Thuman, W. C., and Wiggins, E. J., "Ice Fog as a Problem of Air Pollution in the Arctic," Arctic, Vol. 10, No. 2, 1957, pp. 89-104.
- Sverdrup, H. U., "Austausch und Stabilität in der untersten Luftschicht," (Austausch and Stability in the Lower Layers of the Atmosphere), Meteorologische Zeitschrift, Vol. 53, No. 1, Braunschweig, West Germany, Jan. 1936, pp. 10-15.
- Tajchman, S., "Energie- und Wasserhaushalt verschiedener Pflanzenbestände bei München," (Energy and Water Budget of Different Plants Near Munich), Wissenschaftliche Mitteilungen, No. 12, Meteorologisches Institut, Universität München, Oct. 1967, 95 pp.
- Ullrich, R. B., "Das Temperatur- und Windprofil an der meteorologischen Station beim Forschungsreaktor München," (Temperature and Wind Profiles at the Meteorological Station Near the Munich Reactor), Wissenschaftliche Mitteilungen, No. 13, Meteorologisches Institut, Universität München, Nov. 1967, 57 pp.
- Weller, G., and Schwerdtfeger, P., "Thermal Properties and Heat Transfer Processes of the Snow of the Central Antarctic Plateau," paper presented at the International Symposium on Antarctic Glaciological Exploration, Dartmouth College, Hanover, N.H., Sept. 3-7, 1968.
- Wendler, G., "The Heat Balance at the Snow Surface During the Melting Period (March, April 1966) Near Fairbanks, Alaska," Beiträge zur Geophysik, Vol. 76, No. 6, Leipzig, 1967, pp. 453-460.

[Received September 30, 1968; revised December 30, 1968]